Astronomy & Astrophysics manuscript no. 0341
(DOI: will be inserted by hand later)
February 2, 2008

Does the butterfly diagram indicate a solar flux-transport dynamo?

M. Schüssler and D. Schmitt

Max-Planck-Institut für Sonnensystemforschung*, Max-Planck-Str. 2, 37191 Katlenburg-Lindau, Germany
e-mail: schuessler@linmpi.mpg.de,schmitt@linmpi.mpg.de

Received; accepted

Abstract. We address the question whether the properties of the observed latitude-time diagram of sunspot occurence (the butterfly diagram) provide evidence for the operation of a flux-transport dynamo, which explains the migration of the sunspot zones and the period of the solar cycle in terms of a deep equatorward meridional flow. We show that the properties of the butterfly diagram are equally well reproduced by a conventional dynamo model with migrating dynamo waves, but without transport of magnetic flux by a flow. These properties seem to be generic for an oscillatory and migratory field of dipole parity and thus do not permit an observational distinction between different dynamo approaches.

Key words. MHD — Sun: activity — Sun: magnetic fields — Sun: interior

1. Introduction

In a recent paper, Hathaway et al. (2003, henceforth referred to as HNWR) presented an analysis of the latitude-time diagram of sunspot observations (commonly called butterfly diagram) and suggested that their results provide "strong observational evidence that a deep meridional flow toward the equator is driving the sunspot cycle". This refers to the so-called flux-transport dynamo models, which attribute the equatorward drift of the sunspot zone in the course of the 11-year solar activity cycle to the transport of toroidal magnetic flux towards low heliographic latitudes by an equatorward meridional flow near the bottom of the convection zone, thought to be the return flow of the observed poleward flow in the upper part of the convection zone and at the solar surface. Such physical transport of magnetic flux is not used in the more 'traditional' type of dynamo models, which explain the equatorward drift by a latitudinally propagating dynamo wave and thus do not require a material flow (for a recent comprehensive review of solar dynamo theory, see Ossendrijver, 2003). In this paper we show that the properties of the butterfly diagram analysed by HNWR (drift velocity of the sunspot zone as a function of latitude and its relation to cycle length and amplitude) are well consistent with a dynamo-wave model without meridional flow.

2. Dynamo model and results

We use a dynamo-wave model without meridional flow to obtain a synthetic butterfly diagram whose basic features are consistent with the solar case, i.e., the magnetic field is concentrated in low latitudes, is antisymmetric with respect to the equator, and reverses polarity from one cycle to the next. We then analyse the properties of the synthetic butterfly diagram in an analogous way as HNWR did with the observed data. It is not our intention here to advocate specific dynamo concepts or models, our sole goal is to clarify whether the observations in fact exclude a dynamo-wave model. Therefore, we do not aim at a completely realistic and detailed model for the solar cycle and thus restrict ourselves to a simple quasi-1D $\alpha\Omega$-dynamo model (Schmitt & Schüssler, 1989; Hoyng et al., 1994) driven by radial differential rotation and by an α-effect due to buoyancy instability of the toroidal magnetic field (Schmitt, 1987; Ferriz-Mas et al., 1994). For simplicity, we assume a constant radial gradient of rotation and a cosine-shaped profile of the α-effect extending from 0 to 60 deg latitude. The dynamo amplitude is limited by a nonlinearity mimicking the buoyant loss of magnetic flux from the dynamo region at the bottom of the convection zone. We allow for random fluctuations of the α-effect in order to simulate the irregularity of the solar cycle.

It is customary to take the strength of the toroidal field, B, in the dynamo region as a proxy for magnetic flux eruption and compare latitude-time diagrams of B with the solar butterfly diagram. Fig. 1a shows a section from such a diagram produced by our dynamo model. The contour lines correspond to $\pm 0.3, 0.5, 0.7, 0.9$ times $B_{\max}$, the maximum toroidal field strength reached during the time considered. The drift curves for the individual but-

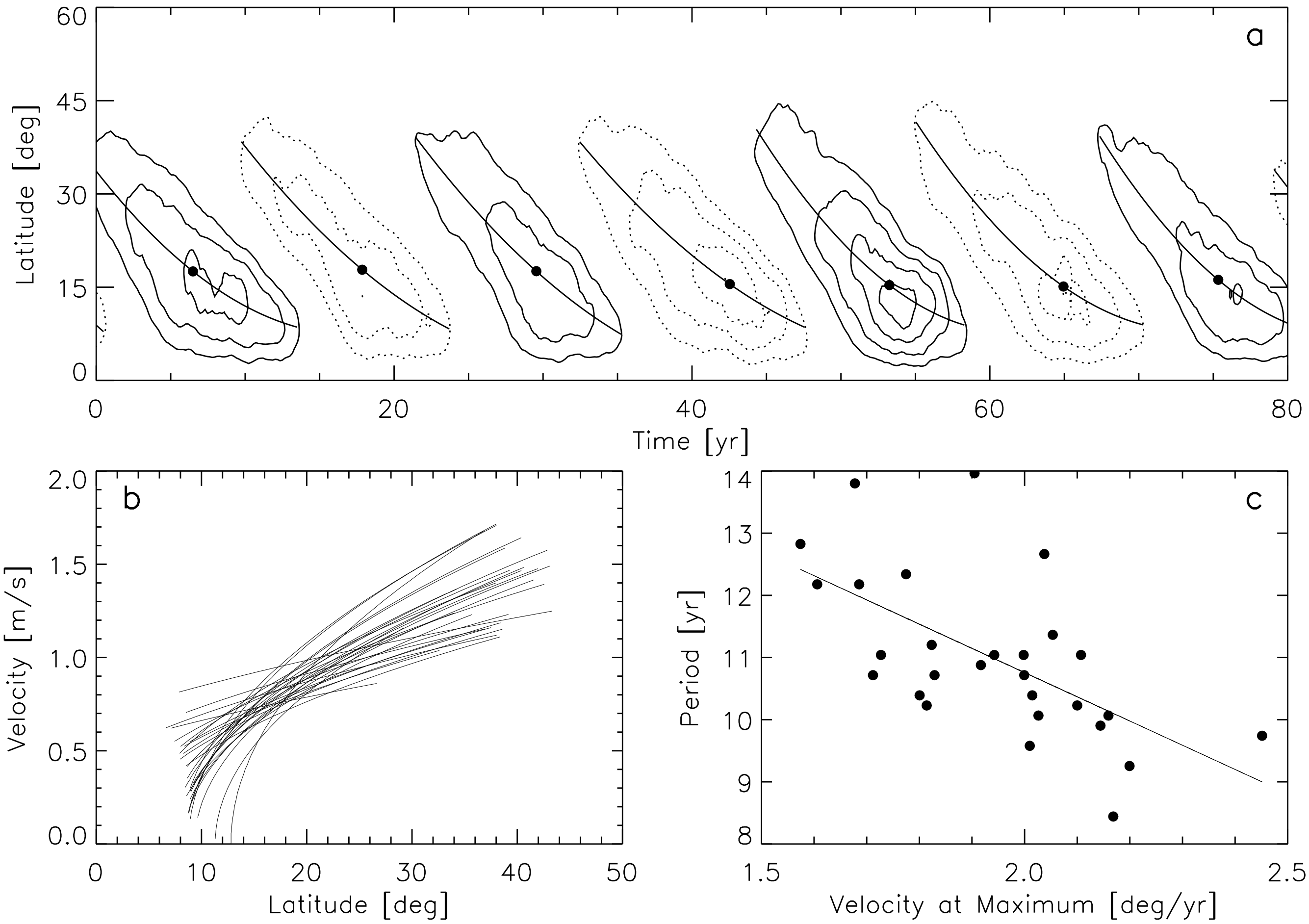

Fig. 1. Results obtained with an $\alpha\Omega$ dynamo model providing latitudinally propagating dynamo waves. **a**: latitude-time diagram (butterfly diagram) of the toroidal magnetic field. Full lines indicate positive, dashed lines negative values. The butterfly wings on the southern hemisphere (not shown) are the opposite-polarity mirror images of the wings shown in the graph. The time unit (diffusion time) has been adjusted to obtain an average cycle period of 11 years for the analyzed time series of 28 cycles. The curved diagonal lines are the drift curves of the butterfly wings with black dots indicating the times of maximum magnetic energy. The variability of the individual cycles results from a stochastic variation of the dynamo excitation. **b**: latitudinal drift velocity as a function of latitude for 28 simulated cycles. The deceleration of the drift near the equator is obvious. **c**: cycle period (time between consecutive minima of the energy in the toroidal magnetic field) vs. drift velocity at the corresponding cycle maximum. The dots indicate the 28 simulated cycles analyzed. The line represents a least-square linear fit.

terfly wings are shown on the same graph. These have been determined in analogy to the procedure used by HNWR. We first define the centroid positions of the wings for each time step as the median position of the latitude profile of $|B|$ between the outermost contour lines (corresponding to $B = \pm 0.3 B_{\max}$, taken as the threshold for the onset of sunspot activity). A quadratic function is then fitted to the centroid positions for each butterfly wing to obtain the drift curves. The times of maximum energy of the toroidal magnetic field ('sunspot maxima') are indicated by black dots on the drift curves.

Figure 1b shows the profiles of the drift velocity (corresponding to the slope of the drift curves) as a function of latitude for a sample of 28 consecutive butterfly wings, including those shown in Fig. 1a. Comparison with Fig. 3 of HNWR reveals a striking similarity of both figures. In particular, the deceleration towards the equator, which has been taken by HNWR as evidence for the magnetic field being carried by a flow turning upward near the equator, is perfectly reproduced by a dynamo wave in the absence of any meridional flow. The scatter among the curves is caused by the random variation of the dynamo excitation (α-effect) in our model.

A similar agreement between the dynamo-wave model and observation is found concerning the relation between cycle period and drift velocity at activity maximum. Fig. 1c shows a clear anticorrelation between these quantities for the 28 simulated cycles (dots); the correlation coefficient is -0.61 with a $t-$value of 3.9, corresponding to a confidence level of 99.9%. Again, this result is in good

qualitative agreement with the data analysis of HNWR (their Fig. 4). Our dynamo-wave model shows that the anticorrelation between drift velocity and cycle period can be reproduced without any meridional flow that sets the period. In our case, the variation of the cycle period is determined by the stochastically varying dynamo excitation: larger α-effect leads to shorter period, and vice versa.

Note that there is no need for fine-tuning of the model parameters in order to arrive at results that compare well with the observed properties. Our results are robust with respect to variations of our model parameters as long as the butterfly diagrams remain basically solar-like, i.e., antisymmetric, migrating equatorwards, and concentrated towards low latitudes. Otherwise, a comparison with observation would not be meaningful anyway.

3. Discussion

We have demonstrated that the properties of the observed butterfly diagram are consistent with dynamo-wave models as well as with flux-transport dynamos. In fact, these properties (slowing of the drift near the equator and anticorrelation between cycle length and drift velocity) appear to be generic features of a toroidal field of dipole parity (antisymmetric with respect to the equator) performing a periodic equatorward drift. Since such a field vanishes at the equator, the drifting toroidal field patterns in both hemispheres have to stop there. Diffusion then leads to a smooth decrease of the drift velocity when approaching the equator, independent of whether the drift is caused by a material motion (meridional flow) or by a dynamo wave. The anticorrelation of the drift velocity of the butterfly wings with the cycle period is almost trivial and largely independent of the physical ingredients of dynamo models: when the period is shorter, the butterfly wings traverse the latitude range of activity within a shorter time and thus travel with a larger speed.

The relationship between drift rate and cycle amplitudes also discussed by HNWR is equivalent to the well-known (weak) anticorrelation between cycle length and amplitude dating back to the days of Rudolf Wolf (1861). The authors mention as another factor in favor of flux-transport dynamo models that there is a stronger anticorrelation between the cycle length and the amplitude of the *next* cycle. However, for the time interval analyzed by HNWR, the strongest anticorrelation in fact appears between the length of cycle n and the amplitude of cycle $n+3$ (Solanki et al., 2002), which is difficult to explain in terms of *any* existing dynamo model.

We do not claim that our simple dynamo-wave model represents a realistic description of the solar conditions. In fact, the sign reversal of the radial differential rotation in higher latitudes is not included and could possibly (depending on the α-effect, see below) lead to a poleward migrating branch of the dynamo wave. On the other hand, such a branch would probably stay unobservable at the solar surface since the magnetic buoyancy instability at high latitudes sets in only for significantly larger field strength than near the equator (Schüssler et al., 1994; Ferriz-Mas & Schüssler, 1995), so that no large-scale magnetic flux would emerge in the polar regions anyway. The concentration of the α-effect to low latitudes and the choice of its sign (which determines the propagation direction of the dynamo wave) may seem arbitrary, but note that the buoyancy instability of toroidal magnetic field yields an α-effect with a similar low-latitude profile and sign (Schmitt, 1987, 2003). There is even a mid-latitude sign change of the α-effect in that model, which, together with the sign change of radial differential rotation, could again lead to a uniformly equatorward propagating dynamo wave. Anyway, the degree of arbitrariness in our model and parametrization is certainly not larger than that of flux-transport dynamo models, which have to specify the unknown properties of the deep meridional flow (depth extension, flow geometry and speed) in addition to the profile of the α-effect. No existing dynamo model does actually *predict* properties like the cycle length or the latitude extension of the butterfly wings.

4. Conclusion

Results of a simple dynamo model show that the drift velocity of the sunspot zone as a function of latitude and its relation to cycle length and amplitude can be reproduced by a migrating dynamo wave. This casts doubt upon the suggestion of Hathaway et al. (2003) that these properties provide observational evidence for a flux-transport dynamo based upon an equatorward meridional flow in the deep convection zone and that this flow sets the cycle period. In fact, these properties of the butterfly diagram seem to be generic to a field of dipolar parity with equatorward drifting, opposite-polarity branches of toroidal field.

Our result that the butterfly diagram does not permit an observational distinction between dynamo-wave and flux-transport models does not lessen the appeal of the flux-transport dynamo concept. Indeed, the poleward meridional flow in the outer parts of the convection zone is an observed fact and clearly mass conservation requires an equatorward return flow somewhere below. However, whether the properties of this flow meet the requirements of flux-transport dynamo models can only be clarified by helioseismic measurements of the meridional flow throughout the whole convection zone and over a time period of the order of the solar cycle (cf. Haber et al., 2002).

References

Ferriz-Mas, A., Schmitt, D., & Schüssler, M. 1994, A&A, 289, 949

Ferriz-Mas, A. & Schüssler, M. 1995, Geophys. Astrophys. Fluid Dyn., 81, 233

Haber, D. A., Hindman, B. W., Toomre, J., et al. 2002, ApJ, 570, 855

Hathaway, D. H., Nandy, D., Wilson, R. M., & Reichmann, E. J. 2003, ApJ, 589, 665

Hoyng, P., Schmitt, D., & Teuben, L. J. W. 1994, A&A, 289, 265
Ossendrijver, M. 2003, A&AR, 11, 287
Schmitt, D. 1987, A&A, 174, 281
Schmitt, D. & Schüssler, M. 1989, A&A, 223, 343
Schmitt, M. 2003, in Advances in Nonlinear Dynamos, ed. A. Ferriz-Mas & M. Núñez (London: Taylor & Francis), 147
Schüssler, M., Caligari, P., Ferriz-Mas, A., & Moreno-Insertis, F. 1994, A&A, 281, L69
Solanki, S. K., Krivova, N. A., Schüssler, M., & Fligge, M. 2002, A&A, 396, 1029
Wolf, R. 1861, Astr. Mitt. Eidg. Sternwarte Zürich, No 8